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Multiple unit root tests under uncertainty over the initial condition: some powerful modifications

Christoph Hanck

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Abstract We modify the union-of-rejection unit root test of Harvey et al. “Unit Root Testing in Practice: Dealing with Uncertainty over the Trend and Initial Condition” (Harvey, *Econom Theory* 25:587–636, 2009). This test rejects if either of two different unit root tests rejects but controls the inherent multiple testing issue by suitably modifying the critical values to ensure the desired null rejection probability. We evaluate the new tests’ power relative to existing ones’ and to the Gaussian asymptotic power envelope. An empirical application illustrates the usefulness of the new statistics.

Keywords Unit root tests · Meta test · Multiple testing

JEL Classification C12 · C22

1 Introduction

As there is no uniformly most powerful unit root test (Elliott et al. 1996), there is and will be no consensus to always use a single test. Specifically, Müller and Elliott (2003) show the Dickey and Fuller (1979) test (O for OLS detrended) to be powerful if the initial condition of the series is large, while the GLS test of Elliott et al. (1996, Q for quasi-differenced) performs well for small initial conditions.¹ Since the statistics are imperfectly correlated, one test might reject the unit root null while the other does not,

¹ Similar considerations arise under uncertainty over the presence of a deterministic trend. We focus on the problem of uncertainty over the initial condition for brevity, but most conclusions also apply under uncertainty over the trend.

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complicating the test decision. The ‘solution’ to reject if either O or Q reject does not yield a level- α test as it ignores the multiple testing nature of the problem.

Harvey et al. (2009, HLT) propose a level- α ‘Union-of-Rejections’ (UR) test that rejects if either O or Q exceed their α -level critical value adjusted by a suitable constant ψ^α . Building on Bayer and Hanck (2009), we modify their idea by showing that power gains are possible in parts of the parameter space when scaling each critical value by separate constants ψ_O^α , ψ_Q^α . We also use Fisher’s (1932) famous P -value combination test to derive ‘meta’ unit root tests.

The Fisher test is more powerful than the best of the individual tests when these have similar power, and has good power when combining more than two tests. Our modified UR test is most useful when the individual tests’ power differ strongly; its power is always close to that of the better individual test, and slightly higher than HLT’s for moderate and large initial conditions.

Section 2 presents the model and test procedures. Section 3 provides local power results. Section 4 reports the empirical application. Section 5 summarizes and discusses possible further research.

2 Model and combination tests

Assumption 1 specifies the standard DGP considered in this paper.

Assumption 1 For $t = 1, \dots, T$, $y_t = \mu + u_t$, where $u_t = \rho u_{t-1} + \epsilon_t$, $t = 2, \dots, T$. $\{\epsilon_t\}$ is a martingale difference sequence with $(0, \sigma^2)$ and $E e_t^4 < \infty$. The error process satisfies $\epsilon_t = C(L)e_t$ where $C(L) = 1 + \sum_{i=1}^{\infty} C_i L^i$, $C(z) \neq 0$ for all $|z| \leq 1$ and $\sum_{i=0}^{\infty} i |C_i| < \infty$.²

We test $\mathcal{H}_0 : \rho = 1$ against $\mathcal{H}_1 : |\rho| < 1$ using the Dickey and Fuller (1979) test (denoted ξ_O) and the t -ratio of Elliott et al. (1996), denoted ξ_Q . First compute $\hat{u}_t = y_t - \bar{y}$. The t -ratio for \mathcal{H}_0 in the regression $\hat{u}_t = \rho \hat{u}_{t-1} + \sum_{p=1}^P v_p \Delta \hat{u}_{t-p} + \epsilon_t$ gives ξ_O . For Q , let $\bar{\rho}_T = 1 - 7/T$, $z_{1\bar{c}} = z_1$, $y_{1\bar{c}} = y_1$, $z_{t\bar{c}} = 1 - \bar{\rho}_T$ and $y_{t\bar{c}} = y_t - \bar{\rho}_T y_{t-1}$ for $t = 2, \dots, T$. Calculate $\hat{\phi}_{\bar{c}} = \left(\sum_{t=1}^T z_{t\bar{c}}^2 \right)^{-1} \sum_{t=1}^T z_{t\bar{c}} y_{t\bar{c}}$ and $\hat{u}^Q = y_t - \hat{\phi}_{\bar{c}}$. The t -ratio for \mathcal{H}_0 in $\hat{u}_t^Q = \rho \hat{u}_{t-1}^Q + \sum_{p=1}^P v_p^Q \Delta \hat{u}_{t-p}^Q + \epsilon_t^Q$ gives ξ_Q .

Assumption 2 controls, through κ , the magnitude of the initial condition $u_1 = y_1 - \mu$ under $\rho_T = 1 - c/T$, $c > 0$ (Müller and Elliott 2003). It ensures that $u_1 = \mathcal{O}_p(T^{1/2})$ such that u_1 matters for the local distribution. The normality assumption allows to provide a power envelope, see below.

Assumption 2 For $\rho = \rho_T$, $\eta \sim \mathcal{N}(0, \kappa^2)$ and $\omega_\epsilon^2 = \sigma^2 C(1)^2$, u_1 is generated as $u_1 = \eta \omega_\epsilon (1 - \rho_T^2)^{-0.5}$.³

The following Lemma of HLT recalls the local distribution of the ξ_j .

² Assumption 1 rules out drift in y_t . The working paper discusses (similar) results to those below with drift in y_t .

³ HLT find similar results for u_1 fixed, whence we omit a detailed discussion thereof.

Lemma 1 (Harvey et al. 2009) *Under Assumptions 1, 2 and $c \geq 0$, $\xi_O \rightarrow_d (K_c^\mu(1)^2 - K_c^\mu(0)^2 - 1)(4 \int_0^1 K_c^\mu(r)^2 dr)^{-1/2}$ and $\xi_Q \rightarrow_d (K_c(1)^2 - 1)(4 \int_0^1 K_c(r)^2 dr)^{-1/2}$, where $K_c(r) = W(r)$ for $c = 0$ and $K_c(r) = \kappa(e^{-rc} - 1)/\sqrt{2c} + W_c(r)$ for $c > 0$, and $K_c^\mu(r) = K_c(r) - \int_0^1 K_c(s)ds$, $W_c(r) = \int_0^r e^{-(r-s)c} dW(s)$ and $W(r)$ a standard Wiener process.*

Lemma 1 reveals that the ξ_j are differentially affected by κ under $c > 0$. Hence, different tests are powerful for different κ . This is the basis of the combination tests, which aim at more robust, and possibly even more powerful, tests using $\mathcal{J} := \{O, Q\}$. HLT's UR test rejects when ξ_O or ξ_Q exceed adjusted critical values ensuring an overall level- α test. Denote test j 's level- α critical value by cv_j^α . The 'naive' statistic $UR^n := \mathbb{I}\{\xi_O < cv_O^\alpha\} + \mathbb{I}\{\xi_O \geq cv_O^\alpha\} \mathbb{I}\{\xi_Q < cv_Q^\alpha\}$, with \mathbb{I} the indicator function, rejects if $UR^n = 1$. As UR^n is oversized,⁴ HLT suggest to reject if $UR_\psi = 1$, where

$$UR_\psi := \mathbb{I}\{\xi_O < \psi^\alpha cv_O^\alpha\} + \mathbb{I}\{\xi_O \geq \psi^\alpha cv_O^\alpha\} \mathbb{I}\{\xi_Q < \psi^\alpha cv_Q^\alpha\} \quad (1)$$

and ψ^α satisfies $\Pr(\xi_O < \psi^\alpha cv_O^\alpha \cup \xi_Q < \psi^\alpha cv_Q^\alpha) = \alpha$. However, one need not apply ψ^α to both cv_j^α . In fact, there is a continuum of constants $(\tilde{\psi}_O^\alpha, \tilde{\psi}_Q^\alpha)$ yielding level- α UR tests. Let

$$UR_{\psi_{\mathcal{J}}} := \mathbb{I}\{\xi_O < \tilde{\psi}_O^\alpha cv_O^\alpha\} + \mathbb{I}\{\xi_O \geq \tilde{\psi}_O^\alpha cv_O^\alpha\} \mathbb{I}\{\xi_Q < \tilde{\psi}_Q^\alpha cv_Q^\alpha\}$$

and reject if $UR_{\psi_{\mathcal{J}}} = 1$. The admissible tuples ψ^α are implicitly defined by

$$\Pr(\xi_O < \psi_O^\alpha cv_O^\alpha \cup \xi_Q < \psi_Q^\alpha cv_Q^\alpha) = \alpha. \quad (2)$$

For each ψ_O^α , there is exactly one ψ_Q^α such that (2) holds. HLT's solution ψ^α is a special case of (2). The availability of a family of tests raises the issue of which ψ^α to use. We suggest to minimize the number of cases where, given (2), ξ_O and ξ_Q reject under \mathcal{H}_0 , i.e. to make the tests as 'uncorrelated' as possible. Since the tests' properties under local alternatives change continuously from those under \mathcal{H}_0 , a powerful test will result. Concretely, select ψ^α such that

$$\psi_O^\alpha = \arg \min_{\tilde{\psi}_O^\alpha \in [1, \infty)} \left\{ \frac{\Pr(\xi_O < \tilde{\psi}_O^\alpha cv_O^\alpha \cap \xi_Q < \psi_Q^\alpha cv_Q^\alpha)}{\min\{\Pr(\xi_O < \tilde{\psi}_O^\alpha cv_O^\alpha), \Pr(\xi_Q < \psi_Q^\alpha cv_Q^\alpha)\}} \right\}. \quad (3)$$

Table 1 reports the ψ^α .⁵ We find $(\psi_O^\alpha + \psi_Q^\alpha)/2 \approx \psi^\alpha$. Hence, $UR_{\psi_{\mathcal{J}}}$ 'reweighs' the ξ_j .

⁴ Under \mathcal{H}_0 , $\Pr(\xi_j < cv_j^\alpha) = \alpha$. The size of UR^n hence equals $\Pr(\xi_O < cv_O^\alpha \cup \xi_Q < cv_Q^\alpha) = \Pr(\xi_O < cv_O^\alpha) + \Pr(\xi_Q < cv_Q^\alpha) - \Pr(\xi_O < cv_O^\alpha \cap \xi_Q < cv_Q^\alpha) = 2\alpha - \Pr(\xi_O < cv_O^\alpha \cap \xi_Q < cv_Q^\alpha) \geq \alpha$, since $\Pr(\xi_O < cv_O^\alpha \cap \xi_Q < cv_Q^\alpha) \leq \Pr(\xi_j < cv_j^\alpha) = \alpha$.

⁵ It is enough to minimize over ψ_O^α , since ψ_Q^α is uniquely determined by (2). We use a two-dimensional grid search to find (3), and add an ϵ to the numerator to penalize borderline cases in which, due to simulation imprecision of W , the numerator would else be zero and the denominator very small, but positive.

Table 1 UR Correction factors and critical values

α	ψ_O^α for ξ_O	ψ_Q^α for ξ_Q	$cv_{\{O,Q\}}^\alpha$ for $\chi_{\mathcal{J}}^2$
0.01	1.059	1.071	15.730
0.05	1.086	1.110	10.440
0.10	1.095	1.164	8.248

Columns 2 and 3 give the constants to adjust the critical values of the statistics ξ_O and ξ_Q for the UR test (2). The corresponding scaling factors ψ^α from HLT (see (1)) are 1.065, 1.095 and 1.126. Column 4 gives critical values of the Fisher test (4) combining ξ_O and ξ_Q

Remark 1 Bayer and Hanck (2009) show that $UR_{\psi_{\mathcal{J}}}$ with (3) is equivalent to rejecting if the smaller P -value rejects when using as cutoff the level $\alpha' < \alpha$ at which one needs to test to avoid the oversizedness of the ‘naive’ approach. Moreover, they show $UR_{\psi_{\mathcal{J}}}$ to outperform Bonferroni.

Another plausible aggregator for the ξ_j is Fisher’s (1932) famous test P -value combination statistic

$$\chi_{\mathcal{J}}^2 := -2 \sum_{j \in \mathcal{J}} \ln(p_j). \quad (4)$$

$\chi_{\mathcal{J}}^2$ has a well-defined asymptotic null distribution $F_{\mathcal{J}}$ as the ξ_j converge jointly. Since the ξ_j are nuisance parameter free and $F_{\mathcal{J}}$ takes the dependence between the ξ_j into account, so is $F_{\mathcal{J}}$. It is straightforward to combine $|\mathcal{J}| > 2$ tests, see Section 3 for results.⁶ $F_{\mathcal{J}}$ is found by simulating (4). Table 1 reports critical values $cv_{\mathcal{J}}^\alpha$, obtained from 50,000 draws, approximating W with Gaussian random walks of length $T = 1,000$. As the ξ_j correlate positively, a $cv_{\mathcal{J}}^{0.05} > 9.487$, the 5% $\chi^2(2|\mathcal{J}|)$ critical value that applies under independence, is necessary for a level- α test. $\chi_{\mathcal{J}}^2$ rejects whenever both ξ_j reject, as $cv_{\mathcal{J}}^\alpha < -2 \sum_{j \in \mathcal{J}} \ln(\alpha)$, and is consistent, as $p_j = o_p(1)$ and thus $\chi_{\mathcal{J}}^2 \rightarrow_p \infty$.

3 Asymptotic power

We approximate rejection probabilities by simulating 100,000 replications of the distributions in Sect. 2, for $T = 1,000$, $c \in \{0, 1, \dots, 30\}$ and $|\kappa| \in \{0, 0.1, \dots, 6\}$. Figure 1 plots power against $|\kappa|$, for $c = \{10, 20\}$. (The end of sect. 3 discusses $\xi_{\hat{\rho}}$ and $\chi_{\{O,Q,\hat{\rho}\}}^2$.) ξ_Q is more powerful than ξ_O for small $|\kappa|$. The power of ξ_O increases in $|\kappa|$, that of ξ_Q decreases. By Müller and Elliott (2003), $\kappa = 1$ yields asymptotics for samples where u_1 equals one standard deviation of the unconditional distribution of y_t . Thus, ξ_O outperforms ξ_Q for a ‘moderate’ to ‘large’ u_1 . Figure 1 also reports the Gaussian asymptotic power envelope under Assumptions 1 and 2. Specifically, Müller and Elliott (2003, p. 1274) show that the member $Q_a^\mu(c, \kappa^2)$ of the family $Q_a^\mu(g, k)$ is

⁶ This also holds for UR_{ψ} from (1). One can also extend $UR_{\psi_{\mathcal{J}}}$ to $|\mathcal{J}| > 2$, but it is more cumbersome to find ψ^α .

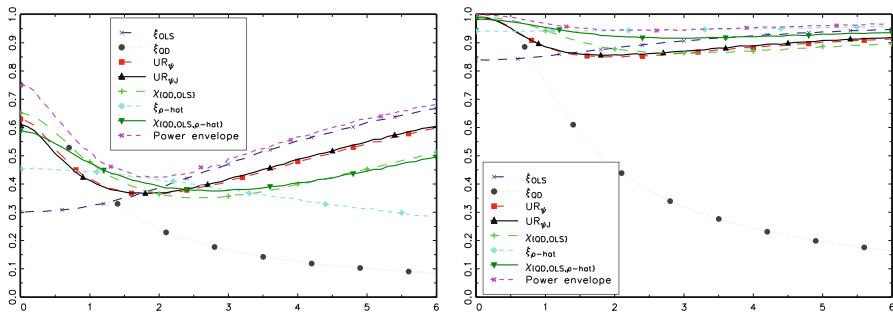


Fig. 1 Local power as a function of $|\kappa|$, $c = 10$ and $c = 20$

point optimal against an alternative having a normal u_1 with multiple κ of the standard deviation of an AR(1) process with $\rho = \rho_T$. Hence, $Q_a^\mu(g, k)$ traces out the power envelope over c and κ .

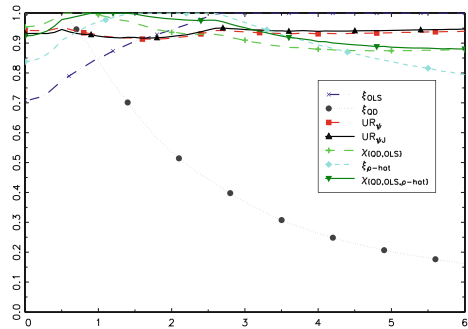
UR_ψ , UR_{ψ_J} and $\chi_{\mathcal{J}}^2$ have power often close to the power envelope. The tests' power is always much closer to that of the better single test. Around the intersection of the individual tests, $\chi_{\mathcal{J}}^2$ even outperforms the individual tests. Intuitively, the ξ_j then often just do not reject, but the joint evidence suffices. The tests are therefore "close to admissible" asymptotically (Müller 2009): Fig. 6 in HLT shows that UR_ψ , UR_{ψ_J} and $\chi_{\mathcal{J}}^2$ are never much less, and sometimes more powerful than $Q_a^\mu(10, 3.8)$. Hence, there cannot be a test with much higher power for *all* κ .

UR_ψ is slightly more powerful than UR_{ψ_J} for small $|\kappa|$. The ranking reverses around $|\kappa| \geq 0.9$, with UR_{ψ_J} outperforming UR_ψ by up to about 1.5% (for $c = 14$ and $\kappa = 3.7$). This pattern is intuitive: Table 1 shows that, relative to HLT, (3) yields a higher (lower) scaling factor for ξ_Q (ξ_O). Since ξ_Q has low power for large $|\kappa|$, little power is lost when increasing ψ_Q^α , whereas some is gained with a lower ψ_O^α . $\chi_{\mathcal{J}}^2$ outperforms UR_{ψ_J} for small-to-moderate $|\kappa| \in [0, 2]$, and in particular when the individual tests have similar power. UR_{ψ_J} outperforms $\chi_{\mathcal{J}}^2$ when the gap between ξ_O and ξ_Q is large. This is intuitive as UR_{ψ_J} looks for *one* rejecting test, to then effectively ignore the other. $\chi_{\mathcal{J}}^2$ uses evidence from both tests, such that a test with low power can lead $\chi_{\mathcal{J}}^2$ to accept. E.g., given $P_1 = 0.03$, $\chi_{\mathcal{J}}^2$ needs $P_2 \leq e^{-[10.440/2 + \ln(.03)]} = 0.18$ to reject. Since no test dominates, Fig. 2 follows HLT in comparing the tests' asymptotic integrated powers over c , scaled relative to the power of the best test for each $|\kappa|$. The *minimum* integrated relative powers are highest for UR_ψ , UR_{ψ_J} and $\chi_{\mathcal{J}}^2$, suggesting robust power of combination tests.

Figure 1 also reports the power of the statistic $\xi_{\hat{\rho}} = T(\hat{\rho} - 1)$ as well as of $\chi_{\{O, Q, \hat{\rho}\}}^2$.⁷ Recall $\xi_{\hat{\rho}} \rightarrow_d (K_c^\mu(1)^2 - K_c^\mu(0)^2 - 1) / (2 \int_0^1 K_c^\mu(r)^2 dr)$. Especially for $c = 20$, adding $\xi_{\hat{\rho}}$ makes $\chi_{\mathcal{J}}^2$ superior to UR_ψ and UR_{ψ_J} : as $\xi_{\hat{\rho}}$ then has high power across

⁷ We also tried tests such as MSB, the weighted symmetric test (Pantula et al. 1994), R (Bhargava 1986), R/S or the MAX-test (Leybourne 1995). However, these tests' local power is similar to that of ξ_Q , so that adding these to $\chi_{\mathcal{J}}^2$ does not improve the performance of $\chi_{\mathcal{J}}^2$. Detailed results are available.

Fig. 2 Asymptotic relative integrated powers against $|\kappa|$



$|\kappa|$, $\chi^2_{\{O,Q,\hat{\rho}\}}$ all but avoids the power dip for intermediate $|\kappa|$ observed for UR_{ψ} and $UR_{\psi,\mathcal{T}}$. Conversely, it is unsurprising that UR_{ψ} and $UR_{\psi,\mathcal{T}}$ outperform $\chi^2_{\{O,Q,\hat{\rho}\}}$ for larger $|\kappa|$ as they are less affected by ξ_Q .

4 Recursive testing for Purchasing Power Parity

We study whether the tests mitigate the effect of the initial condition. Specifically, we recursively test whether the Purchasing Power Parity (PPP) relation holds between the United States and the United Kingdom. Let p_t be the log UK price index in period t , p_t^* the log price index of the US and s_t the log nominal Pound-Dollar exchange rate. The real exchange rate is then given by

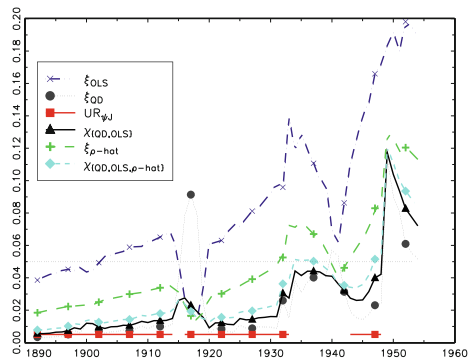
$$r_t = p_t - p_t^* - s_t. \quad (5)$$

Tests of the PPP hypothesis are naturally formulated as unit root tests on r_t (Rogoff 1996). In line with standard practice, a constant is used in the deterministic part. We use the annual dataset of Taylor (2002), which is useful as it covers a long period, 1892 to 1996. We gradually increase the starting date of the test sample from $t = 1892$ to 1955, yielding sample sizes between 105 and 42.

Figure 3 plots the tests' P -values, and whether $UR_{\psi,\mathcal{T}}$ rejects. P is chosen with the MAIC (Ng and Perron 2001). As power grows in T , all P -values unsurprisingly trend upwards. ξ_O rarely rejects, whereas ξ_Q does. The decisions do, however, also reverse: ξ_O rejects for samples starting during WW I, while ξ_Q does not, plausibly a period with a large u_1 . Conversely, the rejections of ξ_Q during the calm late 19th/early 20th century is in line with the good power of ξ_Q for small u_1 .

Given only the ξ_j , one would be unsure about the properties of r_t . Except for samples starting after WW II, the combination tests typically reject. Moreover, $UR_{\psi,\mathcal{T}}$ and the $\chi^2_{\mathcal{T}}$ are less sensitive to the often arbitrary choice of starting date than the single tests, exhibiting none of the abrupt shifts e.g. during WW I. Finally, for 1933–1943, both $\chi^2_{\mathcal{T}}$ reject while $UR_{\psi,\mathcal{T}}$ does not, as one marginal single rejection and one modest acceptance suffice for a rejection for the former, but not the latter.

Fig. 3 P -values of US/UK real exchange rate unit root tests as a function of the starting date. Visible stretches of $UR_{\psi, \mathcal{T}}$ correspond to rejection periods. The horizontal dotted line is at $\alpha = 0.05$



5 Conclusion

We propose meta tests to combine individual unit root tests. The tests take into account the multiple testing nature of running several tests and hence control size. They suitably aggregate the individual statistics or modify their critical values, based on an idea of Harvey et al. (2009). We find the tests to have good power that may be close to the Gaussian asymptotic power envelope.

These combination procedures are applicable more generally. Further work might hence develop such procedures for other problems without a uniformly most powerful test. Examples from the unit root literature include tests against nonlinear alternatives (e.g. Kruse 2011), tests which allow for general heteroscedasticity (e.g. Haldrup 1994) or panel unit root tests (e.g. Jönsson 2008).

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